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PERFORMANCE REPORT OF THE SOLEIL MULTIPOLE INJECTION KICKER

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Abstract

A Multipole Injection Kicker (MIK) was installed in a short straight section of the SOLEIL storage ring and successfully commissioned in 2021. A small horizontal orbit distortion in the micrometer range was achieved outperforming the standard bump-based injection scheme installed in a 12 m long straight section. Refined studies have been conducted to fully understand and further improve the performance of the device. Indeed, a novel generation of the MIK will be the key element for the injection scheme of the SOLEIL Upgrade. We report simulation studies and the latest MIK experimental performance. Both injected and stored beam-based measurements were performed using new types of diagnostics with turn-by-turn capability (Libera Brillance+ BPM, KALYPSO: 2x1D imaging). The residual perturbations on the beam positions and sizes were measured; the magnetic field of the MIK device was reconstructed. An unexpected kick was detected in the vertical plane and an active correction implemented to cancel the resulting perturbation.

INTRODUCTION

After the successful commissioning of the Multipole Injection Kicker (MIK) at Synchrotron SOLEIL in the first half of 2021 [1], a finer tuning of the MIK has achieved unprecedented performance well below the tolerances which define transparent Top-Up injections: closed orbit distortions (CODs) lower than 2 to 3% of the rms stored beam size. Newly commissioned state-of-the-art diagnostics were required to measure such low COD levels. Beam position monitors (BPMs) connected to the improved Libera Brillance Plus electronics (LBP) [2] and the ultra-fast camera KALYPSO [3] provided turn-by-turn measurements of the transverse beam positions and sizes with high resolution. Turn-by-turn loss maps were also measured with the advanced beam loss monitors (BLMs) [4, 5]. The measurements were correlated to the simulation data computed with the refined Accelerator Toolbox (AT) [6] model of the storage ring.

We report the latest performance of the MIK, both from the simulation and experimental point of view, as well as a presentation of the new high-performance diagnostics.

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TOP-UP OPERATION AT SOLEIL

Top-Up Injection in the SOLEIL Storage Ring

SOLEIL is a 3rd generation storage ring-based synchrotron light source implementing a 110 MeV linear accelerator, a full energy booster injector and a 354 m long storage ring. The latter is based on a modified Chasman-Green lattice providing a 3.9 nm rad horizontal emittance at 1% coupling (see Table 1), in which a 2.75 GeV electron beam is stored. It provides synchrotron radiation, from infrared to hard X-rays, to 29 beamlines surrounding the storage ring. In the perspective of achieving sub-micrometer stability of the stored beam position, the Top-Up mode has been operated since 2009. Top-Up injection relies on a four kicker bump-based scheme installed in a 12 m long straight section [1]. Despite many efforts devoted to tuning the four kicker magnets to avoid residual CODs [7, 8], intrinsic design limitations prevent transparent injections. Thus, in the scope of R&D purposes, a single MIK was commissioned successfully in 2021 in order to prove it could be an alternative solution to the standard injection scheme [1].

Table 1: Main Parameters of the SOLEIL Storage Ring

Parameter	Value
Energy (GeV)	2.75
Circumf./Rev. period (m/μs)	354.1 /1.18
Harmonic number	416
RF Frequency/Voltage (MHz/ MV)	352.2 / 2.8
Natural emittance (nm rad)	3.9
Energy spread (%)	1.016×10^{-3}
Hor./Vert. betatron tunes	(18.156, 10.228)
Corrected hor./vert. chromaticities	(1.2, 2.4)

Innovative Injection Scheme for Top-Up Operation

The MIK was developed and built by SOLEIL in the scope of collaboration with MAX IV (2012-2017) [9, 10]. Its design was inspired by the non-linear kicker developed by BESSY [11]. The mechanical and magnetic design of the MIK as well as its assembly and integration into the SOLEIL storage ring are detailed in [1] while its main characteristics are recalled in Table 2.

After the installation of the MIK, the airflow around its vacuum chamber and the heat load dissipation had to be improved by adding extra air turbines [12]. Following the improvement of its cooling system, the MIK quickly reached the expected injection performance. Among the major achievements, we reached a maximum of 97% injection efficiency

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Table 2: Main Parameters of the MIK

Parameter	Value
Nom. supplied volt./current (kV/kA)	10 / 3.3
Pulse duration (µs)	2.4
Magnetic length (mm)	304
Nominal hor. kick at target pos. (mrad)	2.2
Target hor./vert. position at MIK (mm)	10.3 / 0.0

for the bare lattice, in agreement with the simulation data. However, during the summer of 2021 one of the standard 1.71 T dipole was replaced by a permanent-magnet based 2.8 T superbend [13]. Although the tunes and chromaticities were adjusted to their values preceding the commissioning of the superbend, its strong sextupolar component reduced the dynamic aperture of the bare lattice (−15 to 13 mm hor. and ±2.6 mm vert.), decreasing the injection efficiency to 85% (80% with the standard injection scheme). Following the commissioning of the superbend, the inner horizontal scraper was inserted further down to 20 mm to protect the MIK from decay losses. The vertical scrapers remained at ±3 mm, with which the overall scraper setting provides sufficient protection while maintaining injection efficiency and beam lifetime compatible with operation.

SIMULATION

The MIK injection is accurately modeled with AT. It allowed the definition of the optimal parameters of the ideal MIK setup and predicted the reduction of the betatron oscillations of the injected beam [1]. The superbend was added to the simulated lattice and the loss rate indeed increased from 1% to 12% (40% coupling of the injected beam) due to the reduction of the dynamic aperture. The majority of injection losses occurs at tight vertical physical aperture locations of ±5 mm. The simulated data are correlated to the beam loss measurements in the experiment section below.

The model also addressed the residual CODs in the vertical plane. Indeed, a residual dipolar error of 15 µT m/kA, equivalent to a 5.3 µrad vertical kick at 3.3 kA, had been detected at the center of the MIK vacuum chamber before its installation. Beam-based measurements subsequently confirmed this defect. A 25 µm cumulative misalignment of the conductors was simulated and reproduced the horizontal dipolar error. An active correction was simulated to cancel the vertical CODs. The compensation implements a pulsed vertical corrector located in the injection section. The vertical tune was adjusted from ν_z = 10.228 to 10.339 to set the required phase advance between the MIK and the corrector. The required vertical kick to cancel the CODs was estimated to be θ_{corr} = 2.8 µrad. This is shown in Fig. 1.

The feasibility of the correction was then demonstrated experimentally.

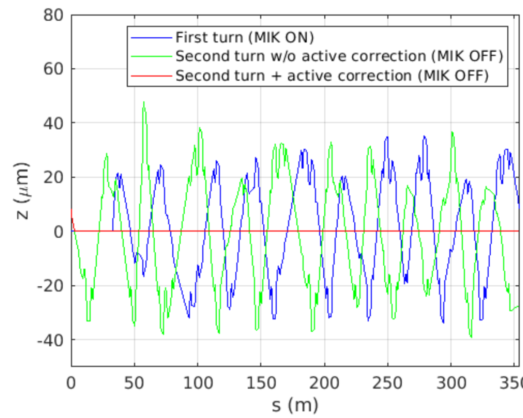

Figure 1: Vertical COD due to the residual dipolar error. The MIK perturbs the beam which exhibits large betatron oscillations during the 1st (blue) and 2nd (green) turns without correction, for ν_z = 0.339. The amplitude of the residual betatron oscillations is canceled when the corrector is switched on during the 2nd turn (red).

HIGH PERFORMANCE DIAGNOSTICS

On the one hand, the LBP electronics has been commissioned and connected to several BPMs [2]. They provide turn-by-turn positions with 5 µm rms resolution, at 15 mA in the one quarter beam filling mode. Additionally, there is no mixing between the turns due to the usual Libera Electron signal processing. On the other hand, a newly commissioned ultra-fast KALYPSO camera has been used to measure the transverse positions and sizes of the stored beam turn-by-turn with unprecedented accuracy [3]. Cylindrical lenses were used to match the synchrotron radiation to the KALYPSO linear sensor while a crossed polarizer enabled to switch from one transverse plane to the other. Besides, turn-by-turn loss measurements that had never been done at SOLEIL before were performed thanks to 80 BLMs. They are distributed in the beam plane at approximately 30 cm from the vacuum chamber on the internal side of the storage ring [4,5]. These are valuable diagnostics without which we would not have been able to go so far in tuning the MIK injection scheme.

EXPERIMENTAL RESULTS

In order to meet the transparent injection tolerances, the stored beam must pass through the magnetic centre of the MIK [1]. To do so, a local horizontal bump of $\Delta x = -200$ µm was created in the MIK, at 15 mA in the bare lattice, in the one quarter beam filling mode (104 continuous bunches). The chromaticities were lowered to ξ_x = 0.6 and ξ_z = 0.8 in order to avoid beam decoherence during the measurements. The minimization of the residual horizontal betatron oscillations is illustrated in Fig. 2.

An active correction was required to cancel the vertical CODs, as neither vertical nor horizontal bumps were of any help. A pulser was specifically built to provide 1.2 µs pulses,

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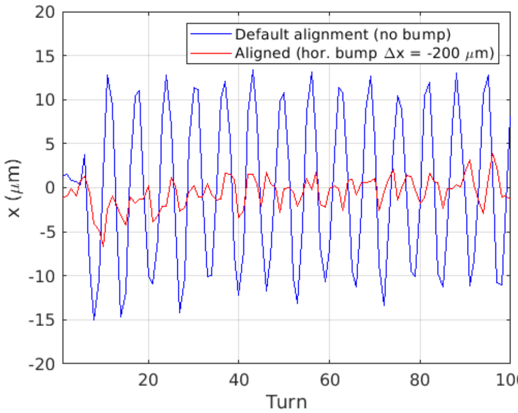

Figure 2: By default the stored beam is not perfectly aligned with the magnetic center of the MIK which results in betatron oscillations when the MIK is triggered (blue). The perturbation is minimized when the beam is centered thanks to a horizontal bump of −200 µm (red). Both signals are averaged over 10 acquisitions.

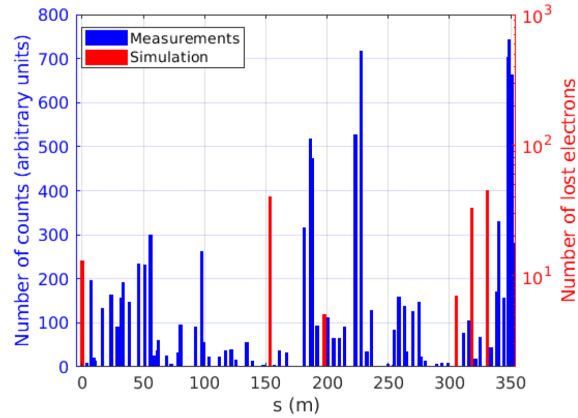

Figure 3: Injection loss map along the ring. The BLM signals (blue bars) give the number of counts, averaged over the first 200 turns in the ring, due to particle showers ignited by electron losses. The simulation (tracking of a Gaussian bunch beam of 10^4 electrons, at 10% coupling) gives the total number of lost electrons over the first 200 turns and their location in the ring (red bars).

equal to one revolution period, with a plateau of 300 ns equivalent to one quarter duration. The corrector kick could be set in the 2 to 12 µrad range. Eventually, the CODs are experimentally canceled for $\theta_{corr} = 4$ µrad, at $\nu_z = 10.374$.

Besides, beam size measurements were performed thanks to the KALYPSO camera. The variations of the transverse stored beam size result from the weak transient quadrupolar fields of the MIK [14]. The experimental setup is unchanged, except the stored beam current is increased to 100 mA. This provides enough resolution and exposure time, with roughly uniform quadrupolar kicks over the bunch train. Under this condition, the bunch-by-bunch transverse feedback is switched on to avoid beam blow up. This does not affect the beam size variations, at first order, since the feedback implements a dipolar correction. The peak variation of the rms horizontal beam size is in the micrometer range. No perturbation occurs in the vertical plane as the quadrupolar fields are only associated to the vertical component of the MIK field. The image processing also allowed to track the beam centroid positions and acknowledge for the effectiveness of the active correction.

On the injection end, the active correction leaves the injection efficiency unchanged (85%). Seven preferential loss areas were detected after the commissioning of the superbend, in correlation with simulations, as illustrated in Fig.3.

CONCLUSION

The MIK outperforms the standard four kickers in terms of stored beam perturbations. The horizontal closed orbit distortions are divided by a factor 100 and are less than 2% of the rms horizontal stored beam size, after the alignment of the stored beam. Moreover, the vertical distortions, specific to the MIK of SOLEIL, were canceled thanks to an active correction. Not only did this compensation preserve the maximum injection efficiency achievable, but it also enhanced the stored beam stability in the horizontal plane. In addition, we measured roughly 1% peak variation in the rms horizontal stored beam size. The booster beam is injected more efficiently using the MIK rather than the usual four kickers, whether it be before or after the commissioning of the permanent-magnet based 2.8 T superbend. All of these results are discussed in more detail along with the corresponding measurements in [15]. Incidentally, preliminary experimental studies conducted with an infrared beamline of SOLEIL revealed first improvements in terms of injection transparency. The former will lead to complementary in-depth studies during summer 2022 to be conducted with other beamlines very sensitive to injection-induced distortions. All these achievements provide enlightening information for the future injection scheme of SOLEIL Upgrade [16–18].

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